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NRL Multisensor Towed-Array Detection System (MTADS) and ORNL High-Sense Helicopter-Mounted Magnetic Mapping (HM3) System

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PREFACE

This document was prepared for the Director of the Environmental Security Technology Certification Program, Office of the Under Secretary of Defense (Environmental Security) under a Task entitled, "ESTCP/SERDP: Assessment of Traditional and Emerging Approaches to the Detection and Identification of Surface and Buried Unexploded Ordnance." We thank Dr. J. McDonald and Dr. H. Nelson at the Naval Research Laboratory, Dr. Dave Bell and Mr. Jeff Gamey at Oak Ridge National Laboratory, and Mr. Scott Millhouse at the Army Corps of Engineers, Huntsville, for data and assistance.

CONTENTS

TABLES

FIGURES

EXECUTIVE SUMMARY

BACKGROUND

The Badlands Bombing Range (BBR) is located in the southwest part of South Dakota. It spans some 300,000 acres and was primarily in use by the Defense Department from World War II until the 1960s. Since that time, parts of the former bombing range, including several impact areas heavily contaminated with ordnance and numerous uncharacterized areas, have been returned to a Sioux tribe, who has an interest in locating ordnance and cleaning the sites. Under funding from the Native American Lands program, the Environmental Security Technology Certification Program (ESTCP) has sponsored demonstrations of advanced sensor technologies in recent years to characterize the ordnance contamination on portions of this site.

Two of these demonstrations will be discussed in this report. The first, conducted in 1997 by the Naval Research Lab, used the Multisensor Towed Array Detection System (MTADS). The second, conducted in 1999 by the Army Corps of Engineers in conjunction with Oak Ridge National Laboratory, used a high-sense helicopter-mounted magnetic mapping (HM3) system. This work is an independent evaluation of the performance of these two advanced sensor systems, both individually and in comparison to one another.

CONCLUSIONS

The most appropriate use for these technologies may be in different missions. The HM3 mounted on a helicopter was originally conceived as footprint reduction tool, where the main requirement is to detect enough ordnance or ordnance-related debris to identify areas that warrant more thorough examination. On the other hand, the MTADS' role is to produce dig lists of individual targets. As such, the ability to do discrimination is not equally important to the two systems. In fact, for the footprint reduction mission, finding ordnance-related clutter may provide as important an indication of an impact area as finding intact ordnance.

The results of the HM3 demonstration were very good, even for detecting individual targets. Using MTADS as a comparison standard for detection and discrimination, we conclude the following:

- On a homogeneous site the Pd achieved by the HM3 on individual targets is about 50 percent of that achieved by the MTADS.
- Only about 8 percent of the apparent clutter that appears in the MTADS dig lists is reported by the HM3.
- Of 22 ordnance items detected and confirmed in the ground truth by HM3, 20 were detected by MTADS. The cause of one missed detection is likely inaccessibility of the area by the vehicle.
- The helicopter-mounted HM3 provides much faster production. We roughly estimate that the HM3 survey rate would be about 10 times faster that the MTADS rate for a large site.
- Cost estimates prepared by the performers indicate that the per acre cost of the MTADS is about 2–3 times higher that those of the HM3. These figures are very rough estimates and may not accurately reflect the cost differences seen in operational surveys.

RECOMMENDATIONS

In the process of this analysis, we have encountered several questions that could not be addressed adequately with that data as it was collected. This is not surprising since the purpose of neither data collection was to provide comparison data. Nevertheless, we offer some suggestions for future similar efforts that would allow for more complete analysis:

- The ground truth from the HM3 excavated targets was inadequate, both for evaluation of this system and for comparison with the MTADS. Although extensive ground truth sampling is expensive, it is critical to obtaining meaningful data for live demonstrations. Sampling of at least 100 targets in future demonstrations is recommended.
- The elapsed time of 2 years between the MTADS and HM3 demonstrations likely had some impact on the system comparisons. This site was in use during the intervening time, when items producing magnetic anomalies may have been added, removed, or displaced by farming activities.
- Conducting excavations between the two demonstrations caused complications. Obviously, this expenditure of resources provided ground truth for only one, instead of both, demonstrations. It also made data analysis for comparisons more time consuming, requiring the tedious separation of

MTADS targets to isolate those left in the ground and available to be detected by the HM3.

- Finally, the selection of targets for ground truthing should be performed with a well articulated purpose in mind. It is difficult to make meaningful comparisons if the goal of one system is to maximize ordnance picks and that of the other is to span the range of signals for analysis purposes.

REVIEW OF UNEXPLODED ORDNANCE DETECTION DEMONSTRATIONS AT THE BADLANDS BOMBING RANGE

NRL Multisensor Towed Array Detection System (MTADS)
and
ORNL High-sense Helicopter-Mounted Magnetic Mapping (HM3) System

A. INTRODUCTION

The Badlands Bombing Range (BBR) is located in the southwest part of South Dakota. Spanning some 300,000 acres, the range was primarily in use by the Defense Department from World War II until the 1960s. Portions of the range were used by the Air Force as bombing targets, and other portions were used for ground-fired weapons. Since that time, parts of the former bombing range, including several impact areas heavily contaminated with ordnance and numerous uncharacterized areas, have been returned to a Sioux tribe, who has an interest in locating ordnance and cleaning the sites. Under funding from the Native American Lands program, the Environmental Security Technology Certification Program (ESTCP) has sponsored demonstrations of advanced sensor technologies in recent years to characterize the ordnance contamination on portions of this site.

Two of these demonstrations will be discussed in this report. The first, conducted in 1997 by the Naval Research Laboratory (NRL), used the Multisensor Towed Array Detection System (MTADS). The second, conducted in 1999 by the Army Corps of Engineers in conjunction with Oak Ridge National Laboratory (ORNL), used a high-sense helicopter-mounted magnetic mapping (HM3) system. The results of these demonstrations were reported separately by their respective performers (Refs. 1 and 2.) Both systems surveyed two common areas, and the purpose of this work is to compare the performance of the two systems.

In 1997, NRL visited the BBR and took survey data on two sites in the Cuny Table area, hereafter referred to as BBR1 and BBR2, using MTADS. Both sites were former impact areas. BBR1 was used chiefly as an aerial bombing target and contained (almost) exclusively M–38 practice bombs and their associated scrap. The M–38 practice bomb, while not carrying a live warhead, does carry a 2-pound black powder spotting

charge. The BBR1 site is divided by a fence along an approximately east-west line bisecting the former bull's-eye. The section north of the fence has been used for livestock grazing and was entirely accessible for both demonstrations. The section south of the fence has been cultivated for farming. As a result, access was somewhat impeded by crops on the south side of the site during the MTADS survey, and excavation of targets was not possible for either demonstration. The BBR2 area contained more varied ordnance, including bombs and rockets.

MTADS is a surface-towed ordnance-detection system that supports both full-field cesium-vapor magnetometer and electromagnetic induction (EMI) arrays. This study is concerned with the magnetometer data only. Typical sensor height above ground for the magnetometers is 0.25 m, typical line spacing is 0.25 m, and typical along-track data density is 0.05 m per point. High-quality differential Global Positioning System (DGPS) geo-referenced digital data is taken at high spatial density and processed using a set of specially developed algorithms to fit magnetometer and/or EMI signatures of operator-selected anomalies. An initial set of targets spanning the range of target sizes and types was used as a training set to guide target selection. The MTADS analysis resulted in dig lists containing 704 magnetometer targets (485 north of the fence and 219 south) for BBR1 and 647 for BBR2. Of these dig list targets, 146 targets on BBR1 and 255 targets on BBR2 were excavated. Details of the sensor and the NRL site activities are provided in Reference 1.

In 1999, ORNL collected DGPS geo-referenced data at the BBR Cuny Table area with a helicopter-mounted HM3 full-field cesium-vapor magnetometer system. Compared with MTADS, the HM3 system produces data with lower spatial density from magnetometers that are deployed at a higher altitude. Typical sensor height above ground is 2 m, sensor spacing is 6 m, and typical along-track data density is 0.5 m per point. Interleaved tracks were flown so that data lanes were separated by a nominal 3 m. With lower sample density and helicopter speeds (~45 kts), the HM3 system provides much faster site coverage than is achievable with a ground-based system. The HM3 system visited five live areas on BBR plus a seeded calibration site. Two of the live areas were the BBR1 and BBR2 sites visited 2 years previously by the MTADS system. This study will concentrate on the BBR1 and BBR2 surveys for platform comparisons and on the calibration area to explore sensitivity on a broader range of targets. Details of the HM3 sensor and the ORNL site activities are provided in Reference 2. The HM3 survey produced dig lists of 520 and 296 targets nominated for digging on BBR1 and BBR2,

respectively. Intrusive sampling was performed on 17 targets on BBR1 and 24 targets on BBR2.

This work is an independent evaluation of the performance of these two advanced sensor systems, both individually and in comparison to one another. First, we look at data from the two individual systems. In the reports generated by the testers, there are some differences in the way that performance is scored and described. This is partly attributed to semantics and partly attributed to the different missions that were originally envisioned for the two systems: the MTADS would be used primarily to do detailed surveys to generate dig lists and the HM3 primarily to do wide-area searches to locate concentrations of ordnance, such as in impact areas, but not necessarily to generate dig lists. Success of these two missions would be measured by different performance metrics. Chiefly, the scrap that is properly considered clutter (false alarms) in a dig list may provide as good a clue to the presence of an impact area as intact ordnance; however, HM3 results were quite good and led us to evaluate its ability to generate dig lists. So, in addition, we look at the differences in performance for the detection of individual targets and the associated false alarms and examine the data for differences caused by the lower sampling density and higher altitude of the HM3 sensor.

B. ANALYSIS OF NRL MTADS DATA

MTADS surveyed the BBR site using magnetometer and EMI systems. For comparison to the HM3 data, this study focuses on the magnetometer data. The MTADS data processing fits the spatial magnetic signature to estimate the depth and size of the object. First, we examined the dig list targets that were excavated to establish ground truth following the demonstration. On BBR1, 146 items were excavated, all north of the fence line, and on BBR2, 225 items were excavated, yielding a substantial body of ground truth data. We examined the target features extracted by NRL testers and the raw signal data for comparison with the ORNL results.

The BBR1 data represents an easier case for discrimination, with both the target and the clutter populations fairly well defined. The former consisted entirely of M–38 practice bombs and the latter mostly scrap from these items. As such, the targets and clutter displayed very different characteristics. The ground-truthed items were divided into clutter and ordnance. The derived features (which include magnetic moment, fit quality, depth, and size) from the NRL data analysis were examined to determine if any provided reliable discrimination. The results are shown in Figure 1. S*ize* and the related *moment* provide fairly reliable discriminants, but for the other parameters, targets and

clutter populations are not as well separated. From here forward, *size* is used for discrimination analyses.

In Table 1, a size threshold of 0.125 is applied to the known target and clutter items. This threshold gives a probability of correct identification of ordnance, given a detection, of 0.97 and a probability of false positive of 0.20. Previous MTADS tests show good probability of detection (near 100 percent) on bombs (Refs. 3 and 4). We conclude that the likelihood of missing a bomb on this site using this threshold is low, that setting a threshold of 0.125 m on size will retain most bombs in the dig lists, but that any list of ordnance-like objects using the best descriminant we have been able to identify will inevitably contain some (20 percent) clutter. This site likely represents the best possible opportunity for discrimination because of the homogeneity of ordnance types and the limited clutter sources.

Table 1. Size Threshold Applied to MTADS Ground Truth on BBR1N

MTADS size threshold says	Total	Is Bomb	Is Not Bomb
Bomb (>0.125)	84	71	13
Not bomb (<0.125)	55	2	53
Total		73	66

Many of the targets selected for the dig lists in the MTADS data analysis were not excavated. The targets that were not dug on the north side of the fence line, as well as all the targets picked on south side of fence line where no digging was possible, were considered using the size discriminant. The distribution plot for the dig list targets that were not dug on the north side of the fence, shown in the upper portion of Figure 2, is very similar to that for the ground-truthed targets north of fence. The same bimodal distribution, which is noted in Reference 1, suggests a similar separation into M–38 targets and clutter. On the south side of the fence, the relative abundances of apparent targets and apparent clutter differ from what was observed in the dug targets on the north side. This is not surprising since the area south of the fence has been cultivated for years. The cultivation likely either brought small clutter items to the surface, where they were cleared by the farmer, or buried them beyond detection range. NRL anecdotally reported an accumulation of scrap along the fence line that is seen in magnetometer images produced by both systems, which was presumably amassed as scrap objects were tossed aside during farming activities.

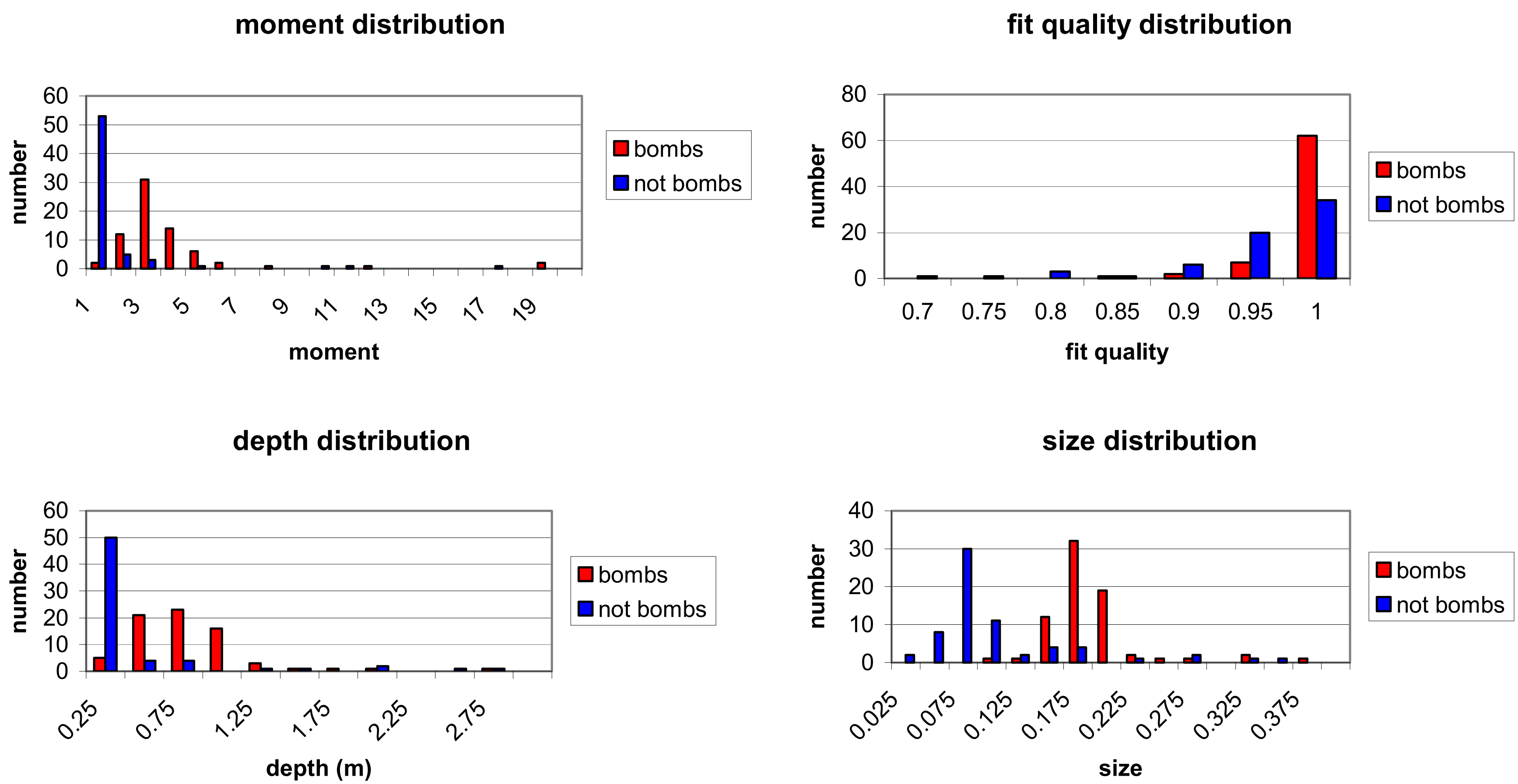
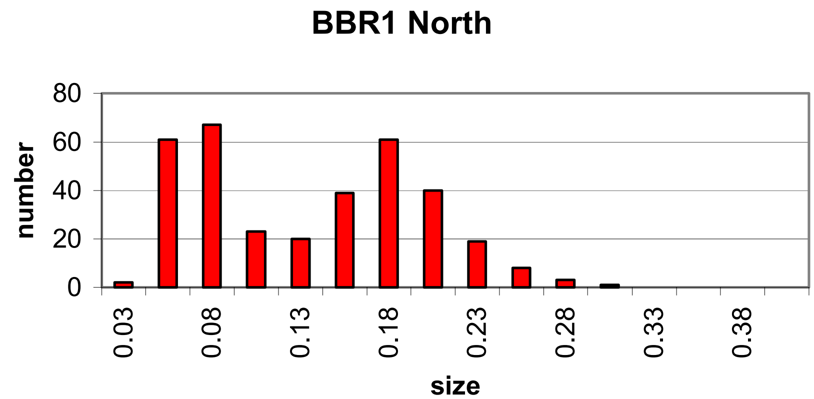


Figure 1. BBR1 Ordnance and Clutter Population Distributions for MTADS-Derived Parameters



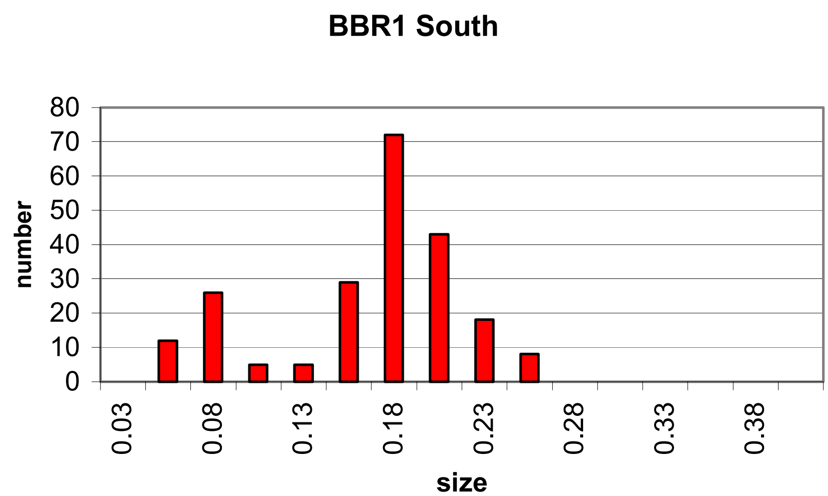


Figure 2. MTADS Size Distributions for Targets Not Dug on BBR1. The upper plot is for the north side of the fence line and the lower plot is for the south side.

Based on the *size* analysis, all the MTADS dig list targets on the BBR1 site were divided into bomb-like and clutter-like, with the threshold set at 0.125 m for subsequent analyses.

The data for BBR2 is more difficult to interpret. This site contains a greater variety of ordnance: the targets dug by MTADS include M–38, small-caliber artillery rounds (SCARs), and 2.75-in. rockets, with one 20-mm and one hole containing two targets. We attempted to do the same exercise for discriminants and were not surprised that it was less successful on BBR2. Figure 3 shows the dug targets separated into ordnance and nonordnance using the size discriminant. The profile of the clutter on BBR2 is not very different from that found on BBR1, but the ordnance does not neatly separate out. If the ordnance is separated by type, the size distributions are as shown in

Figure 4. The SCARs cover a wide range of sizes and the distribution of 2.75 rocket warheads significantly overlaps the clutter. The M–38 bomb size distribution is not very different from what was observed for these targets in BBR1, although the centroid is concentrated at slightly larger sizes. With far fewer M–38s dug on BBR2, it is not clear that this represents any statistically meaningful shift in the population, which would be unlikely in any event.

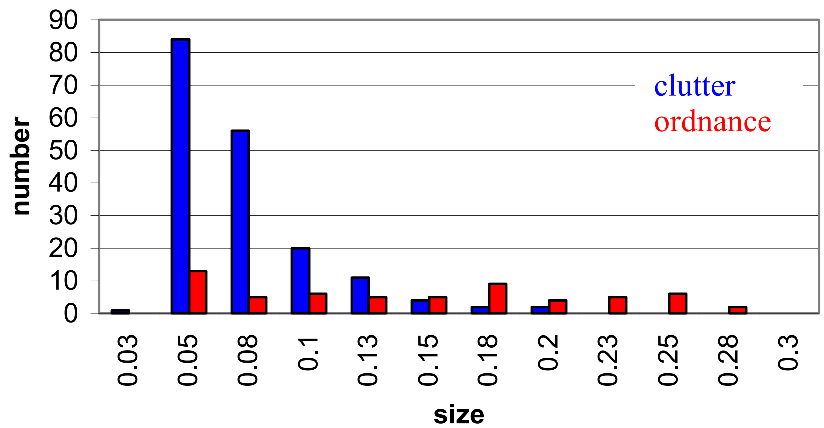


Figure 3. BBR2 MTADS Size Distributions of Target and Clutter

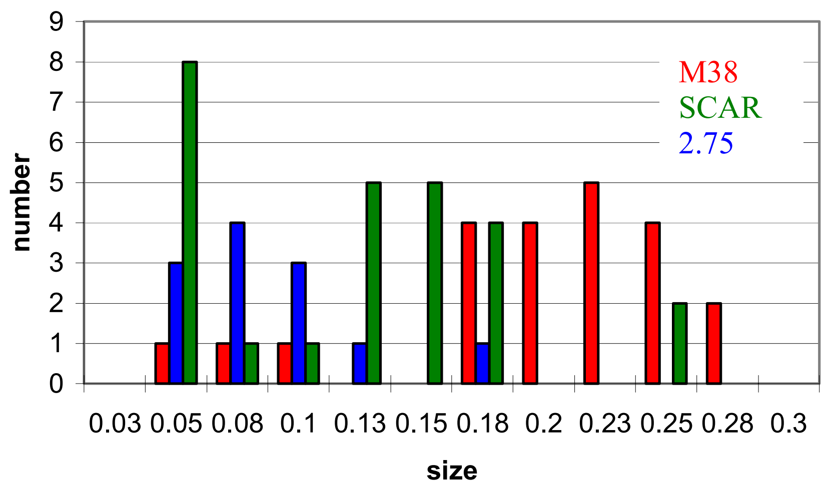


Figure 4. BBR2 MTADS Size Distributions Broken Out by Ordnance Type

C. ANALYSIS OF ORNL HM3 DATA

We performed two types of analyses using the ORNL data. First, using the ORNL picks, we looked at characteristics in analytic signal in an attempt to determine if any discrimination could be performed based on the analysis as presented. Second, in the next section, to compare to MTADS data and to evaluate sensitivity of the system based on the calibration area, we looked at the raw magnetometry data.

The rescoring of the HM3 data was performed to select dig lists from the data. When originally scored by ORNL, all magnetic returns that were reacquired by ground-based sensors were regarded as successful hits, regardless of whether they represented intact ordnance, ordnance-related scrap, or even hot soils. For the most part, this is reasonable (except perhaps for the inclusion of hot soils): since the goal of the work was to characterize impact areas, any ordnance-related scrap could be considered a legitimate target. To generate dig lists, however, we are interested in finding intact ordnance, versus fins and rocket motors, which do not present a hazard. Finally, we also need to select a common terminology and scoring system to do the comparisons to MTADS performance. We opt for the scoring system shown in Table 2. Here, we eliminate the use of the term P_d in Reference 2, since the total number of ordnance items encountered is not known (P_d therefore cannot be determined), and replace it with percent ordnance (the fraction of digs that resulted in ordnance). The primary result of the rescoring is that the percentage of targets corresponding to ordnance (referred to as P_d in Ref. 2) is lower, and the percentage of false positives is higher.

Table 2. ORNL HM3 Results as Rescored by IDA

Area	Anoms	Digs	M38	2.25 in.	Frag or Scrap	Hot Soils	No Contact	% Ord	% FP
1	49	17	13	0	1	1	2	76	24
2	33	24	16	4	4	0	0	83	17

We begin with a brief summary of the HM3 data. The system records full-field magnetometer data, which is processed using the Geosoft tool to obtain what is referred to as an analytic signal, essentially a horizontal gradient.[1] All decisions regarding target declarations were made by the ORNL team on the basis of the analytic signal. Initial target selection was done by amplitude thresholding on the analytic signal and selecting

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1 The analytic signal is computed as $AS = \left[(dT/dx)^2 + (dT/dy)^2 + (dT/dz)^2\right]^{1/2}$ where T is the total field. The x and y derivatives are computed spatially from the grid, and the z derivative is computed using a Fourier transform.

everything over 1.0 nT/m as a potential target. From this list, targets were selected for a dig list, which was then further downselected for actual digs. The number of dug targets was extremely limited and spanned the range of signal amplitudes (i.e., the dug targets do not represent all the strongest signals).

If the goal is to generate dig lists, it will be important to identify a discriminant to distinguish ordnance from clutter. In the case of the HM3 data, the only parameter calculated in the original data analysis was analytic signal. Unfortunately, few targets were dug following the HM3 survey. On BBR1, only 17 excavations were conducted, and all were in the part of the site north of fence line. Figure 5 shows distributions of analytic signal for ordnance and nonordnance ground truth. There is no potential to draw a line separating the two populations, which significantly overlap. This finding is not surprising, since it involved no more than creating an amplitude threshold: depending on target size and depth and sensor geometry, one expects the amplitudes to span the space.

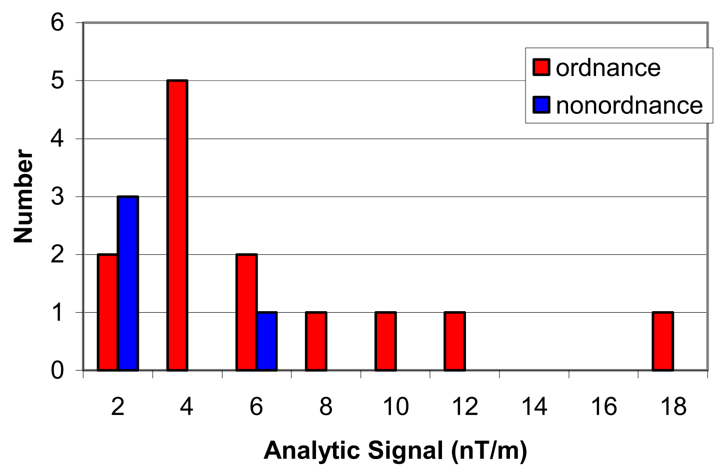

Figure 5. BBR1 HM3 Analytic Signal Distribution

The results for the analytic signal on BBR2 are similar. As shown in Figure 6, the ordnance and nonordnance (clutter) show almost total overlap in this parameter. The dug targets on BBR2 included only M–38 practice bombs and 2.25-in. rockets.

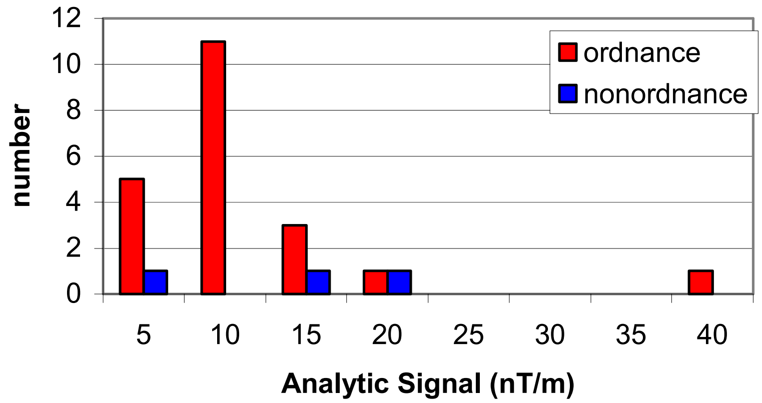

Figure 6. BBR2 HM3 Analytic Signal Distribution

D. CROSS COMPARISONS—WHO FOUND WHAT?

Figure 7 shows the targets selected by MTADS and the HM3 on BBR1. This plot includes all targets picked by each sensor, regardless of whether they were dug or whether the target attributes indicated that they were clutter-like or bomb-like. The linear feature that runs approximately along the Y = 0 line is the fence separating the north and south sides. The MTADS target picks are separated into those dug and not dug. The plot shows some commonality of targets. This is an important initial result: the two data sets were not submitted in common coordinate systems, so some coordinate conversions were required to enable comparisons. Both data sets were originally taken in using GPS in WGS84 latitude and longitude; however, ORNL used the NAD27 datum for transformation to Universal Transverse Mercator (UTM) coordinates, and NRL used NAD83. Initial attempts at direct conversion between the two data sets were not successful, resulting in significant offsets. The likely cause of the difficulty was an error in the NAD27 data used by ORNL, which was noted in the original report by the performers, but the root cause of it was never determined. We requested that ORNL provide locations of target picks in the original lat/long WGS84 and successfully used a commercial software package by Blue Marble Geographics (Ref. 5) to do the conversion to NAD83. Then, ORNL NAD83 coordinates were transformed into MTADS local coordinates for convenience, and all subsequent analyses were performed on these data sets. After the initial difficulties, the matching of targets between the two data sets gave us confidence that the conversions were done correctly.

All performance comparisons in this document must be considered in the context of the philosophies of target selection employed by the two performers, which may skew the results considerably. The MTADS target list on BBR1 includes the initial targets selected for the training set, as well as targets from the entire site selected based on the training set results. Target picks on the entire site were not weeded to select only large bombs, but to mirror the profile of the training set. On BBR2, the MTADS list concentrated on sampling smaller items. The HM3 targets were selected using a simple amplitude threshold in the analytic signal data. Obvious nonordnance sources of anomalies, such as fences and posts, were manually removed from the dig lists.

Figure 8 shows the MTADS and HM3 picks on the north side of the fence in BBR1. Again, the MTADS target picks are divided into those that were dug and not dug. Recall that the MTADS targets were dug prior to the HM3 survey, so none of the MTADS dug targets is expected to be observed in the HM3 data. The MTADS targets that were not dug were separated into bomb-like and clutter-like based on the size threshold of 0.125 m selected above. These locations were then examined for coincident target declarations in the HM3 data. Table 3 shows the results.

Of the 172 bomb-like targets MTADS detected but did not excavate, 95 were detected by the HM3 (55 percent). Of the 173 clutter-like targets MTADS detected but did not excavate, only 13 (8 percent) were detected by the HM3.

Figure 9 shows the MTADS and HM3 target picks for BBR1 south of the fence line, none of which were excavated. Again, the MTADS picks are divided using the size threshold into bomb-like (>0.125) and clutter-like (<0.125) and analyzed as for the north side. Table 4 shows the results. The outcome is similar, with HM3 detecting 45 percent of the bomb-like MTADS targets and 8 percent of the clutter-like MTADS targets.

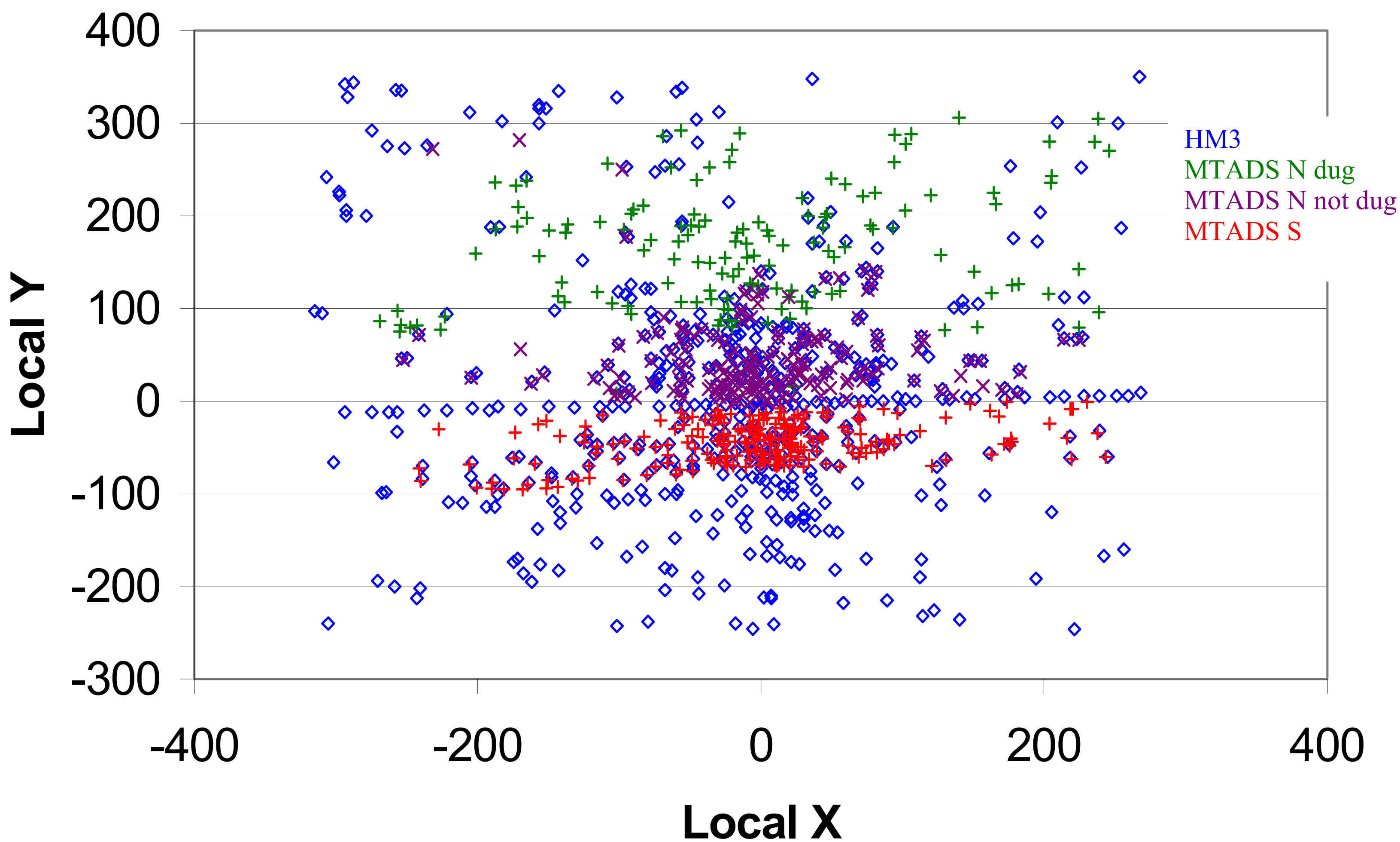

Figure 7. BBR1 MTADS and ORNL Dig List Picks. All targets are plotted in the MTADS local X and Y coordinates, where X runs east-west, Y runs north-south, and (0,0) is located approximately at the center of the bombing target bull's-eye.

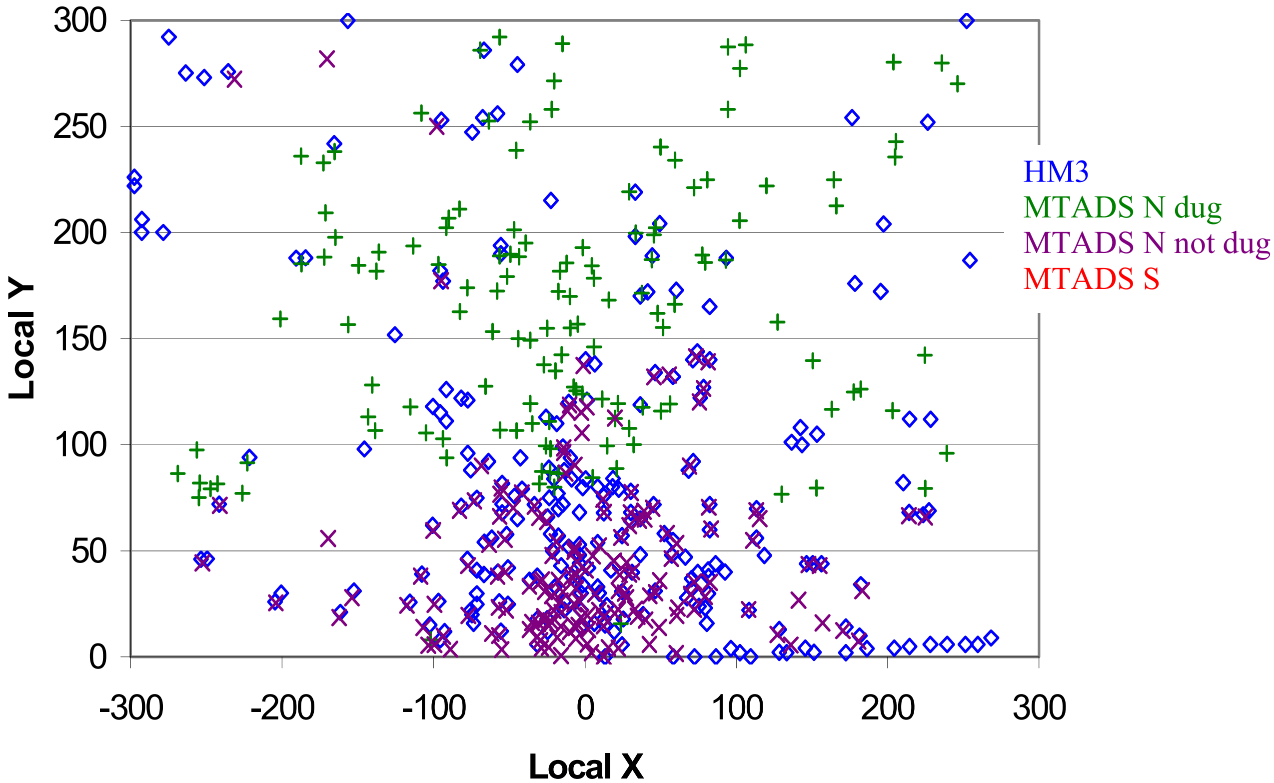

Figure 8. BBR1 MTADS and HM3 Dig List Picks North of the Fence

Table 3. BBR1 North MTADS Target Picks Not Excavated vs. HM3 Target Picks[1]

	MTADS	HM3 Target	No HM3 Target
Bomb-like (size >0.125)	172	95	77
Clutter-like (size <0.125)	173	13	160

[1] Based on a threshold of 1 nT/m in the analytic signal.

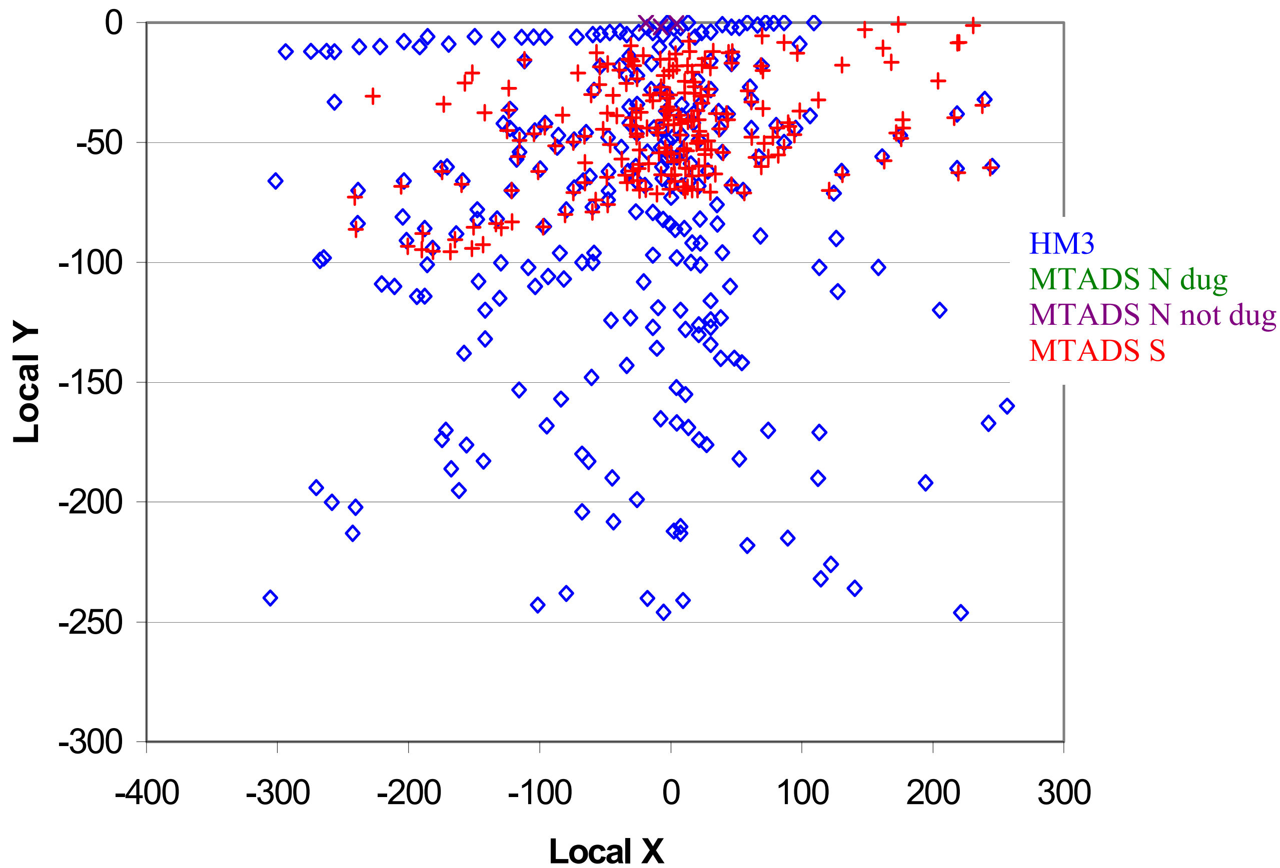

Figure 9. BBR1 MTADS and HM3 Target Picks South of the Fence

Table 4. BBR1 South MTADS Target Picks vs. HM3 Target Picks

	MTADS	HM3 Target	No HM3 Target
Bomb-like (size >0.125)	170	77	93
Clutter-like (size <0.125)	48	4	44

We also compared the HM3 dig results with the MTADS targets not dug for coincident detections. Figure 10 shows the HM3 dug targets labeled to show the ground truth determined by digging at BBR1. Overlaid on the HM3 ground truth and marked as bomb-like and clutter-like are the MTADS targets not dug. Note that few targets were dug based on the HM3 picks and further, no effort was made to pick targets believed to be bombs. The results are summarized in Table 5. MTADS visited a smaller area than the HM3. Ten of the eleven practice bombs found in the HM3 ground truthing in the common area were detected and selected for the MTADS target list. The bomb at approximately X = –150 m, Y = 100 m, which does not appear in the MTADS target list,

is in an area where the MTADS anomaly map shows a small patch of ground where no data was taken because of an obstacle to driving. With MTADS capable of a higher sample density and making measurements at significantly closer standoff distance, it would be surprising for MTADS to miss anything found by HM3. The MTADS did not select any targets at the locations where the HM3 ground truth resulted in no contacts or fins. At the location of the single “hot soil” reported by the HM3, the MTADS reported a target which falls into the “clutter-like” category base on size discrimination.

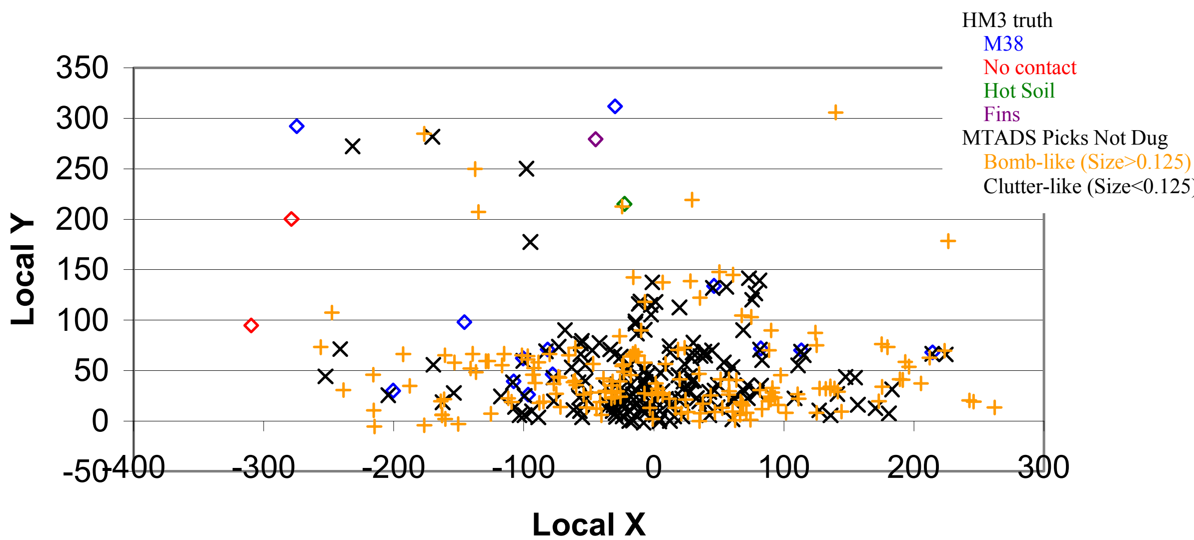

Figure 10. HM3 Ground Truth and MTADS Dig List Picks Not Dug

Table 5. BBR1 HM3 Ground Truth from Excavated Targets vs. MTADS Targets Not Excavated

	HM3	MTADS			
		Bomb-like	Clutter-like	No Detect	No Visit
M38	13	10	0	1	2
No Contact	2	0	0	2	0
Hot Soil	1	0	1	0	0
Fins	1	0	0	1	0

The same analysis was done on BBR2. We compared the HM3 dug targets with the MTADS targets picks that were not dug. Figure 11 shows a plot of all the dig list picks with HM3 ground truth indicated. The results are summarized in Table 6. Because of the lack of success in identifying a reliable discriminant in the MTADS data for BBR2,

no attempt was made to differentiate MTADS picks into ordnance-like and nonordnance-like. Of 21 total ordnance items found in the HM3 ground truthing, MTADS had the opportunity to detect 10 (i.e., the locations of the other 11 items were not visited in the MTADS survey). Of these 10 opportunities, MTADS reported target picks at 9. The missed item was a rocket.

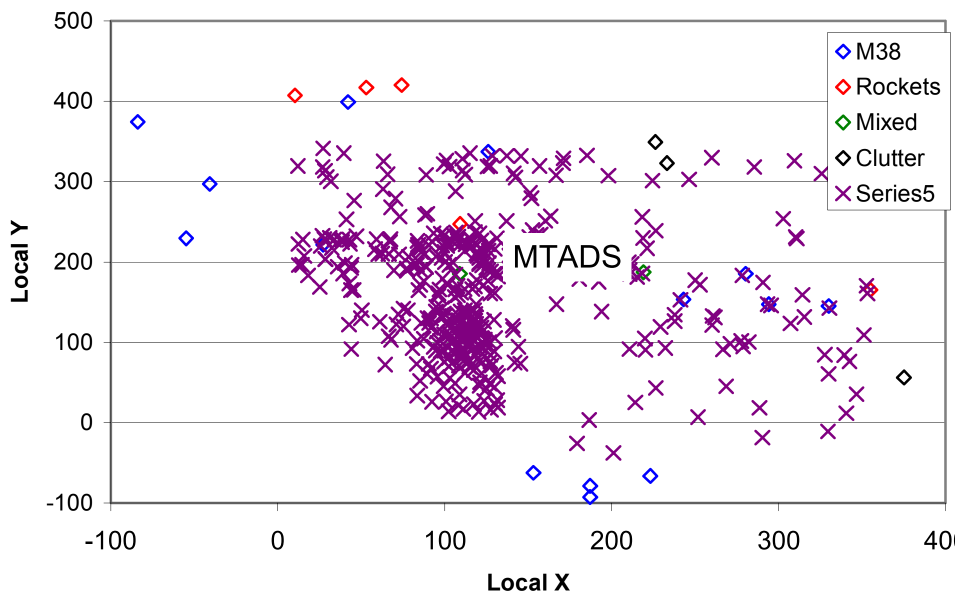

Figure 11. BBR2 HM3 Ground Truth and MTADS Target Picks Not Dug

Table 6. BBR2 HM3 Ground Truth vs. MTADS Targets Not Excavated

	HM3	MTADS		
		Detect	No Detect	No Visit
M38	14	6	0	8
Rockets	5	1	1	3
Mixed	2	2	0	0
Clutter	3	0	1	2

E. TARGET COMPARISONS—CAN WE SAY WHY?

Further coordinate conversion problems were encountered in the raw data analysis. We were supplied with the NAD27 UTM coordinates for the raw data, and attempts to convert directly from NAD27 to NAD83 resulted in an offset. We used several points widely spaced in the image to estimate the true offset by comparing their locations to the correct locations of targets in the dig list derived from direct conversion of the WGS84 GPS data described above. Additional corrections were applied to the raw

data locations. These corrected UTM NAD27 locations were then transformed into NAD83, which were then transformed into MTADS local coordinates for analysis.

1. Site Coverage

Given the sensor layout and modes of operation, the data densities for MTADS and the HM3 are very different. We attempt to quantify the effect of this difference and examine its impact on data. Consider BBR1. The site is gridded into squares, beginning with 1 m on a side and growing to 5 m on a side. For each grid size, the fraction of the grid squares visited by each sensor was counted (see Table 7). Figure 12 shows HM3 coverage rates for various grid sizes.

Table 7. Coverage Rates for Various Grid Sizes

Grid Size (m)	MTADS	HM3
1	99.9	33.1
2	100.0	58.8
3	100.0	76.4
4	100.0	88.1
5	100.0	95.0

2. Individual Signature Comparisons

A few targets were selected for direct comparison of signatures in the sensor data. These included two M–38 bombs, one at a depth of 3.5 ft (1.1 m) and the other at 1.5 ft (0.5 m), and one false alarm that corresponded to hot soil. Figures 12–14 show chips of the HM3 total field data, the HM3 analytic signals, and the MTADS magnetometer data for the selected targets. First, we considered the maxima in the total field signals, which are shown in Table 8. Since none of these signals has magnitude near the noise floor of the instruments, the differences in maximum signals should be dominated by the proximity of the sensors to the targets. From the vertical component of the distance alone (i.e., depth of target plus height of sensor), there is a factor about 10 to about 30 difference in expected signal strength between the HM3 and the MTADS total field measurements for these targets. The lower spatial density of the HM3 data on average will easily increase this significantly. Other effects such as the relative orientation of the sensors and targets are not considered, but are likely to be significant. Generally, a factor of about 100 or more difference is seen in the maxima.

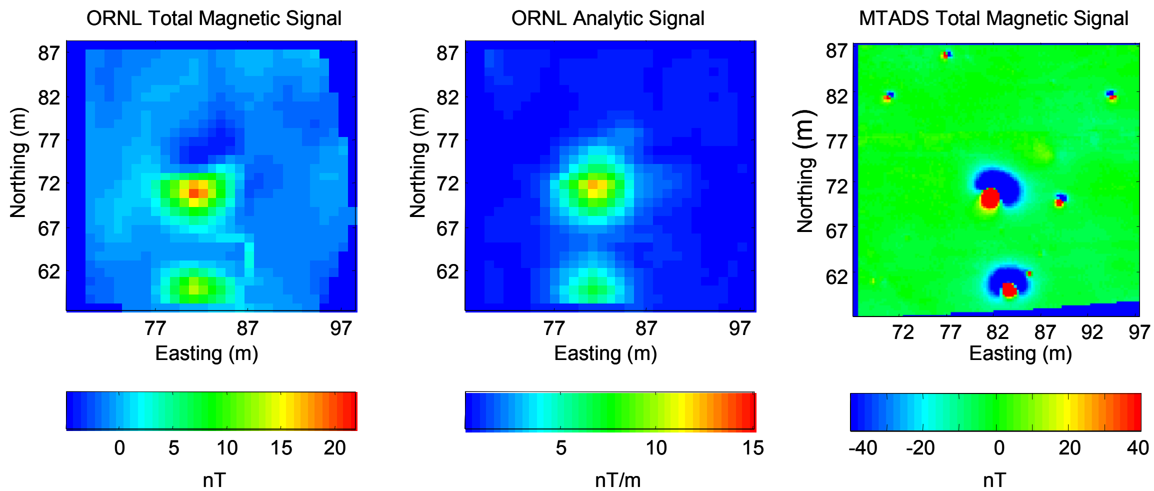

Figure 12. HM3 Total Magnetic Signal, HM3 Analytic Signal, and MTADS Magnetic Signal for BBR1 HM3 Target 1039, an M–38 Practice Bomb Buried at 1.1 m

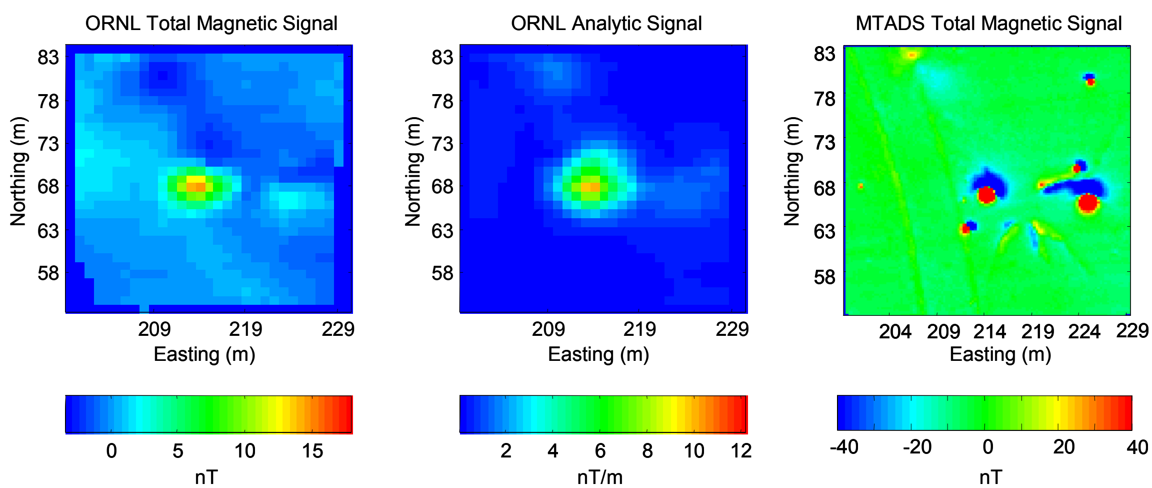

Figure 13. HM3 Total Magnetic Signal, HM3 Analytic Signal, and MTADS Magnetic Signal for BBR1 HM3 Target 1064, an M–38 Practice Bomb Buried at 0.5 m

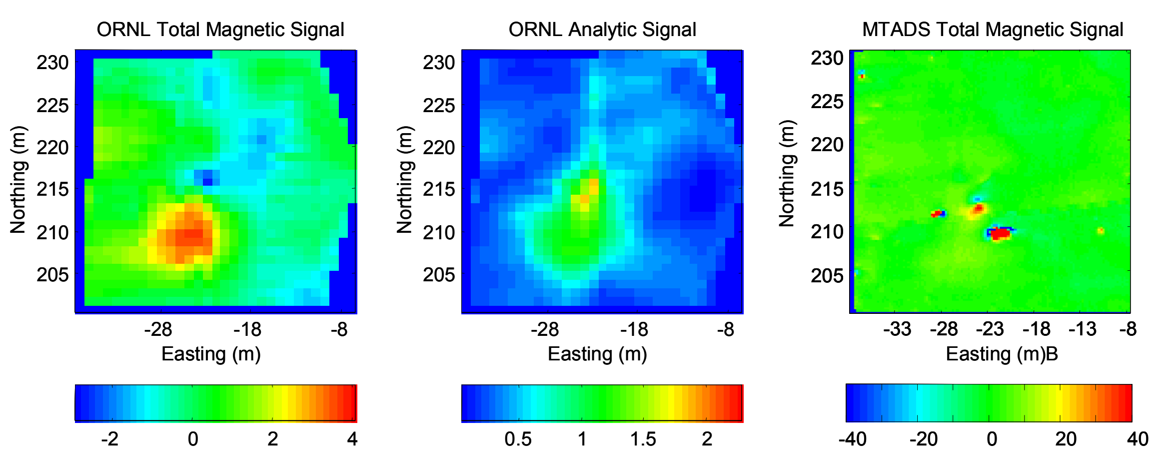

Figure 14. HM3 Total Magnetic Signal, HM3 Analytic Signal, and MTADS Magnetic Signal for BBR1 HM3 Target 1380, Which Resulted from Magnetic Soil at 1.3 m

Table 8. Summary of Sensor Data for Selected Targets on BBR1

Target # (ORNL)	Type	Depth (m)	Sensor Distance Ratio[1]	MTADS Mag (nT)	HM3 Mag (nT)	HM3 Analytic Signal (nT/m)
1039	M38	1.1	13	3967	22	15
1064	M38	0.5	33	1694	18	12
1340	Hot soil	1.3	11	487	5	2.7

[1] Sensor distance ratio is calculated using the vertical dimension only. The height of the sensor above ground is added to the target depth, and the ratio of the HM3 distance to the MTADS distance is cubed.

F. LOCATION ACCURACY

As reported in Reference 1, the MTADS location accuracy, gives an average miss distance of 12 cm, with 90 percent of the targets detected within 22 cm. No similar analysis is provided in Reference 2 for the HM3 system; however, because of the difference in data densities, we expect considerably larger location errors compared with MTADS. Using the 39 targets excavated on BBR1 and BBR2, we calculated that the average positional error was 0.5 m and that 90 percent of the targets were found within 1 m.

To estimate the relative accuracy of the HM3 and MTADS, we examined an area of BBR1 with a relatively low density of picked targets and set a 10-m distance as a cutoff in matching the HM3 picks to the MTADS picks. Within the resulting matches, the mean distance from MTADS to HM3 location is 3.0 m, the maximum radial offset occurs at 7 m, and only 7 percent of the hits cross correlate at 1 m separation. This is in stark contrast to the accuracy observed in the HM3 ground truthing. We have been unable to unambiguously identify the cause of this discrepancy, although it likely lies in the coordinate conversion difficulties described above. Residual errors in the coordinate conversion process could result from our calculations, although this seems unlikely for the target pick locations used in the location analyses because their X,Y coordinates were calculated directly from the WGS84 lats and longs, which we have no reason to believe contained errors. Another possibility is that any systematic errors in the HM3 location data were obscured by the empirical location corrections applied at the time of the excavations.

G. PRODUCTION RATES AND COSTS

Accurate estimates of production rates and costs will be difficult to obtain for both systems from this demonstration because there is no accounting breakdown of time spent on various tasks. This presents several problems: the MTADS demonstration included an EMI survey and the time to analyze these data is not broken out; the level of analysis done by the two performers was quite different, both in terms of the type of analysis and the previous experience; and the number of targets excavated differed greatly.

We attempted to segregate the impact of a towed platform versus an airborne platform on survey rate from the other unknown parameters. To do this, we looked at the specifications of both systems as reported in this demonstration and previous MTADS demonstrations to estimate survey time on a relatively large site of 1 km^2. For the HM3, we use the quoted helicopter speed of 20 m/sec, the sensor spacing of 6 m on the platform, and the interleaved survey pattern to give 3-m nominal data line spacings. With these parameters, 1.8 hours would be required to survey 1 km^2. This estimate does not include additional time required for turns. For MTADS, we use the 2-m array width (with tracks correspondingly separated by 2 m) and a travel speed of 2.5 m/s to estimate that the 1 km^2 site would require 55 hours of survey time, also not including turn-around time.

For this demonstration, the MTADS total cost was $377,296. If the excavation costs of $169,096 and the reporting costs of $24,000 are removed, the MTADS costs for the deployment, survey, and analysis parts of this demonstration were $184,200. (Note that this does not separate out the costs of the EMI work.) The MTADS surveyed a total of more than 150 acres for a cost of $1,222 per acre. For the HM3, the total costs of this demonstration were $220,000 to survey 287 acres, for a cost of $766 per acre.

Both performers in their respective demonstration reports made estimates of the time and cost required to survey large sites. These are summarized in Table 9. We used the MTADS projections for a 1,000-acre site. We did not do any analysis to verify the projections of either performer. As would be expected, the projected costs per acre for both performers are lower for production work than those incurred for this demonstration.

Table 9. Summary of Performer Projections of Cost and Production Rate for Large Sites (Refs. 1 and 2)

	Cost ($/acre)	Production Rate (acres/day)
MTADS (1,000-acre site)	570	10
HM3	200	200

The specific projection numbers probably do not have much meaning as they will depend on the size of the site, the type and density of ordnance contamination, the deployment costs, and many other parameters in any real clean-up operation. There is no doubt, however, that the helicopter platform will be faster by a factor of 10 or more, and it is also likely to be less expensive.

H. CONCLUSIONS

First, it is important to note that the most appropriate use for these technologies may be in different missions. The HM3 mounted on a helicopter was originally conceived as a footprint-reduction tool, where the main requirement was to detect enough ordnance or ordnance-related debris to identify areas that warrant more thorough examination. On the other hand, the MTADS' role is to produce dig lists of individual targets. As such, the ability to do discrimination is not equally important to the two systems. In fact, for the footprint-reduction mission, finding ordnance-related clutter may provide as important an indication of an impact area as finding intact ordnance.

The results of the HM3, however, are very good, and it is tempting to ask how it would do in producing dig lists. This report looks at what is possible using the current data:

- On a homogeneous site, the P_d achieved by the HM3 on individual targets is about 50 percent of that achieved by the MTADS.
- Only about 8 percent of the apparent clutter that appears in the MTADS dig lists is reported by the HM3.
- Of 22 ordnance items detected and confirmed in the ground truth by HM3, 20 were detected by MTADS. The cause of one missed detection is likely inaccessibility of the area by the vehicle.
- The helicopter-mounted HM3 provides much faster production. We roughly estimate that the HM3 survey rate would be about 10 times faster than the MTADS rate for a large site.
- Cost estimates prepared by the performers indicate that the per acre cost of the MTADS is about 2–3 times higher that those of the HM3. These figures are very rough estimates and may not accurately reflect cost differences seen in operational surveys.

In the process of this analysis, we have encountered several questions that could not be addressed adequately with that data as it was collected. This is not surprising, since the purpose of neither data collection was to provide comparison data.

Nevertheless, we offer some suggestions for future similar efforts that would allow for more complete analysis.

- The ground truth from the HM3 excavated targets was inadequate, both for evaluation of this system and for comparison with the MTADS. Although extensive ground truth sampling is expensive, it is critical to obtaining meaningful data for live demonstrations. Sampling of at least 100 targets in future demonstrations is recommended.
- The elapsed time of 2 years between the MTADS and HM3 demonstrations likely had some impact on the system comparisons. This site was in use during the intervening time, when items producing magnetic anomalies may have been added, removed, or displaced by farming activities.
- Conducting excavations between the two demonstrations caused complications. Obviously, it was a great expenditure of resources that provided ground truth for only one, instead of both, demonstrations. It also made data analysis for comparisons more time consuming, requiring the tedious separation of MTADS targets to isolate those left in the ground and available to be detected by the HM3.
- Finally, the selection of targets for ground truthing should be performed with a well articulated purpose in mind. It is difficult to make meaningful comparisons if the goal of one system is to maximize ordnance picks and that of the other is to span the range of signals for analysis purposes.

GLOSSARY

BBR	Badlands Bombing Range
DGPS	differential Global Positioning System
EMI	electromagnetic induction
ESTCP	Environmental Security Technology Certification Program
HM3	high-sense helicopter-mounted magnetic mapping
MTADS	Multisensor Towed-Array Detection System
NRL	Naval Research Laboratory
ORNL	Oak Ridge National Laboratory
SCAR	small-caliber artillery round
UTM	Universal Transverse Mercator map coordination system

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13. ABSTRACT *(Maximum 180 words)*

This paper reports on demonstrations of two sensor systems conducted at the Badlands Bombing Range in South Dakota. The first demonstration, conducted in 1997 by the Naval Research Laboratory, used the Multisensor Towed Array Detection System. The second demonstration, conducted in 1999 by the Army Corps of Engineers in conjunction with Oak Ridge National Laboratory, used a high-sense helicopter-mounted magnetic mapping system. The systems were evaluated individually and compared to each other. Based on this analysis, the paper concludes that the most appropriate use for the technologies may be in different missions and recommends that revamped testing, with better ground truth, be conducted.

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